

Disclaimer: Reference herein to any specific commercial company, product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government of the Department of the Army (DoA). The opinions of the authors expressed herein do not necessarily state or reflect those of the United States Government or the DoA, and shall not be used for advertising or product endorsement purpose.



Reduced-Order Modeling Method for Fatigue Life Prediction of Hybrid Electric Vehicle Batteries

Sung-Kwon Hong, Bogdan I. Epureanu,
Matthew P. Castanier

Report Documentation Page				Form Approved OMB No. 0704-0188	
Public reporting burden for the collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington VA 22202-4302. Respondents should be aware that notwithstanding any other provision of law, no person shall be subject to a penalty for failing to comply with a collection of information if it does not display a currently valid OMB control number.					
1. REPORT DATE 13 JUL 2012		2. REPORT TYPE Briefing		3. DATES COVERED 01-06-2012 to 01-07-2012	
4. TITLE AND SUBTITLE REDUCED-ORDER MODELING METHOD FOR FATIGUE LIFE PREDICTION OF HYBRID ELECTRIC VEHICLE BATTERIES				5a. CONTRACT NUMBER W56H2V-04-2-0001	
				5b. GRANT NUMBER	
				5c. PROGRAM ELEMENT NUMBER	
6. AUTHOR(S) Matt Castanier; Sung-Kwon Hong; Bogdan Epureanu				5d. PROJECT NUMBER	
				5e. TASK NUMBER	
				5f. WORK UNIT NUMBER	
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) University of Michigan,1011 N University Ave,Ann Arbor,Mi,48109				8. PERFORMING ORGANIZATION REPORT NUMBER ; #23127	
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000				10. SPONSOR/MONITOR'S ACRONYM(S) TARDEC	
				11. SPONSOR/MONITOR'S REPORT NUMBER(S) #23127	
12. DISTRIBUTION/AVAILABILITY STATEMENT Approved for public release; distribution unlimited					
13. SUPPLEMENTARY NOTES Submitted to 2012 NDIA Ground Vehicle Systems Engineering and Technology Symposium August 14-16 Troy, Michigan					
14. ABSTRACT briefing charts.					
15. SUBJECT TERMS					
16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT Public Release	18. NUMBER OF PAGES 10	19a. NAME OF RESPONSIBLE PERSON
a. REPORT unclassified	b. ABSTRACT unclassified	c. THIS PAGE unclassified			

- Objectives
- Structural Battery Model
- Parametric Reduced-Order Models (PROMs)
 - Numerical Results: Forced response of academic battery pack
 - Full-order models
 - PROMs
 - Numerical Results: Detection of highest vibrating cells
 - Three cases of variations
 - Statistical Results
- Conclusions

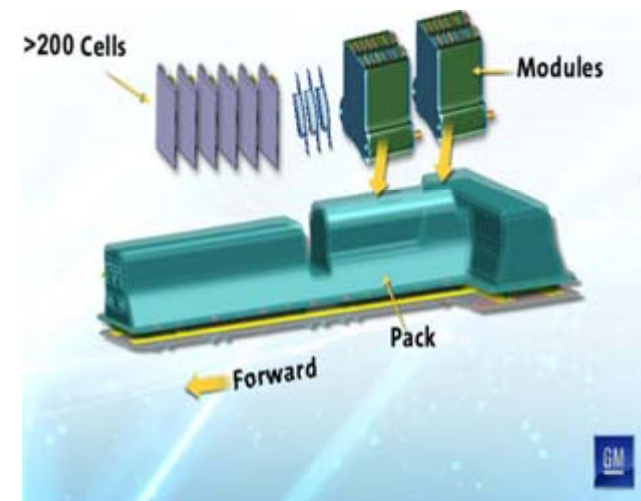
Objectives

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Gain better understanding of structural dynamics featuring very **high modal density**
 - Special attention to **hybrid electric vehicle (HEV) battery packs**
 - For high modal density, **small cell-to-cell structural variations** have **very large consequences** for the dynamics of the pack
- Develop an **efficient and accurate** computational method for predicting the **structural dynamic response** of HEV batteries
- Enable **fatigue life predictions** by performing **statistical dynamic response calculations**



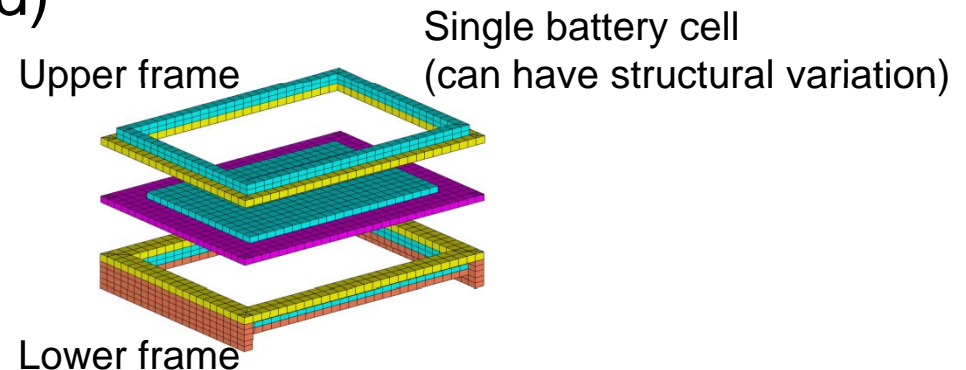
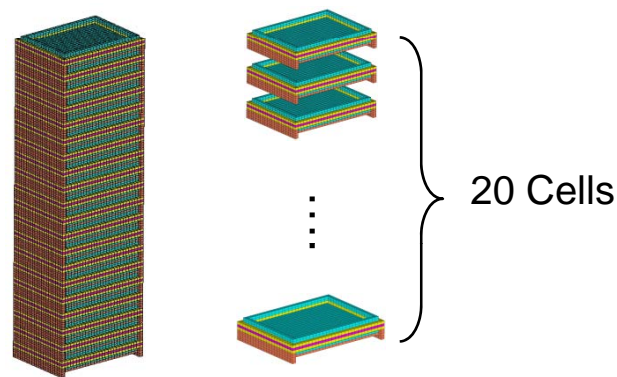
<http://jcwinnie.biz/wordpress/?p=2477>



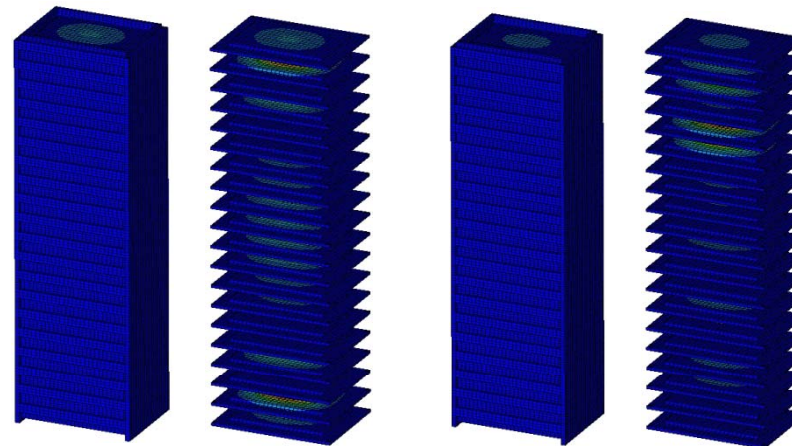
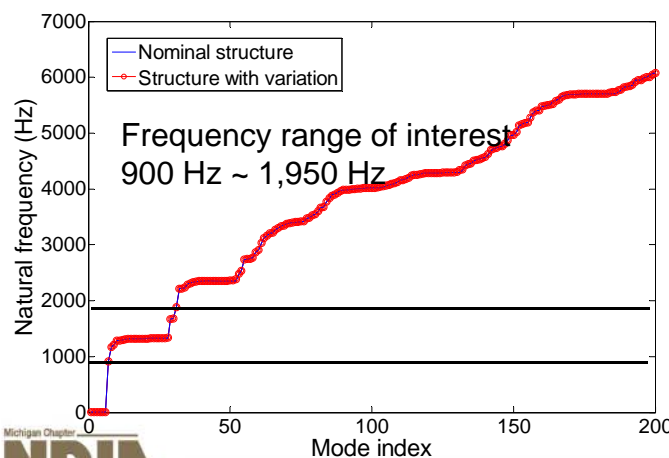
Academic Battery Model

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

- Battery has 20 cells (stacked)



- Dynamic response (natural frequencies and mode shapes)



Mode shapes
are sensitive
to variations,
but natural
frequencies
are not

Parametric Reduced-Order Models (PROMs): Key Ideas

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

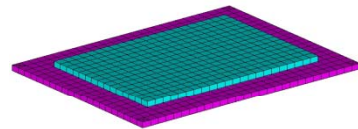


- Modes (Φ_M) of a **structure with small parametric variations** and high modal density (e.g., a batter pack) can be approximated using a **linear combination of modes (Φ_T) of the structure with nominal parameters**

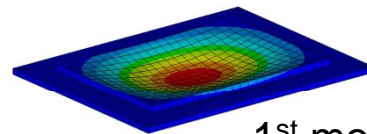
$$\mathbf{M}\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + \mathbf{K}\mathbf{x} = \mathbf{F} \rightarrow \Phi_T \text{ (Mode for nominal structure)}$$

$$(\mathbf{M} + \mathbf{M}^\delta)\ddot{\mathbf{x}} + \mathbf{C}\dot{\mathbf{x}} + (\mathbf{K} + \mathbf{K}^\delta)\mathbf{x} = \mathbf{F} \rightarrow \Phi_M \text{ (Mode for structure with variations)}$$

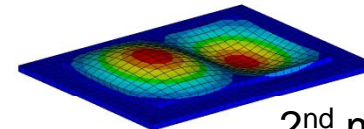
- The **motion in each of the cells** is plate-like with fixed boundary



Single battery cell
with fixed boundary
(nominal)



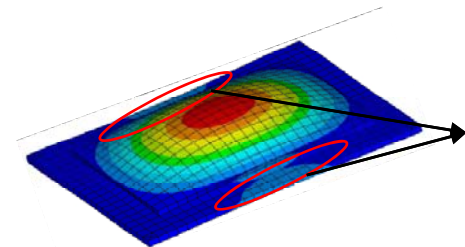
1st mode of cell



2nd mode of cell

The effects of parameter variability are captured by
cantilevered plate modes

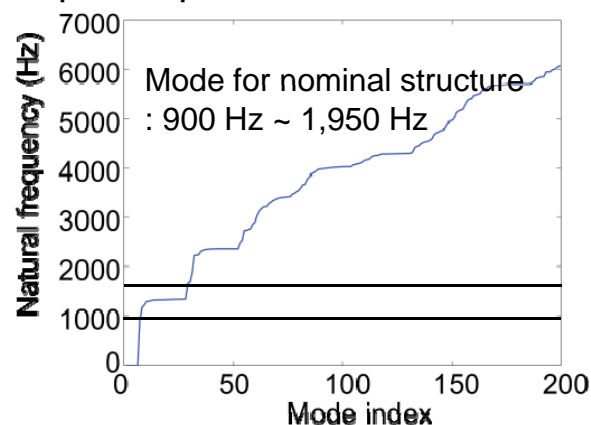
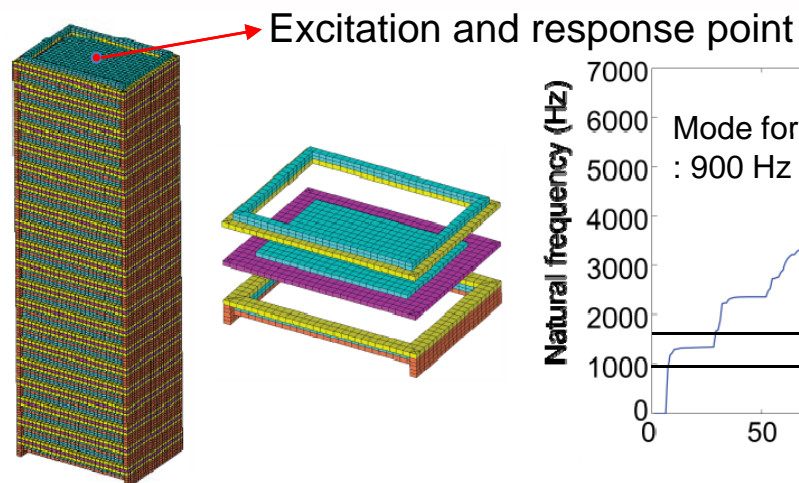
- To capture the effect of the motion of the boundary of battery pack, cantilevered plate mode with **boundary (frame) displaced as in the nominal modes** are used



Boundary
displacement

Numerical Results: Full-Order Models

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

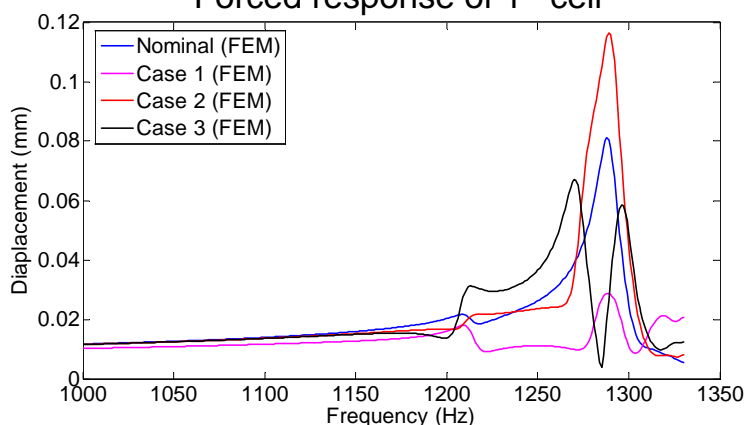


Three cases of Young's modulus variations in various cells

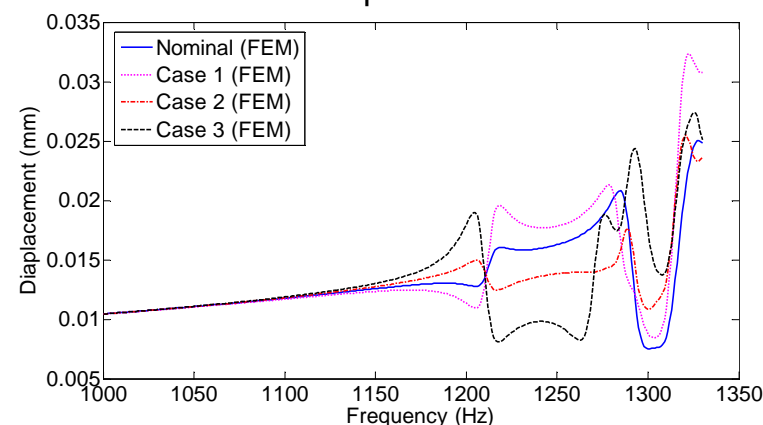
Case 1		Case 2		Case 3	
Cell	Variation	Cell	Variation	Cell	Variation
1	5%	4	10%	3	3%
5	-7%	7	-8%	9	-5%
12	1%	10	3%	13	2%
16	3%	19	-5%	20	-5%

Total DOFs: **208,752**, 20 battery cells are stacked
Material: Steel

Forced response of 1st cell



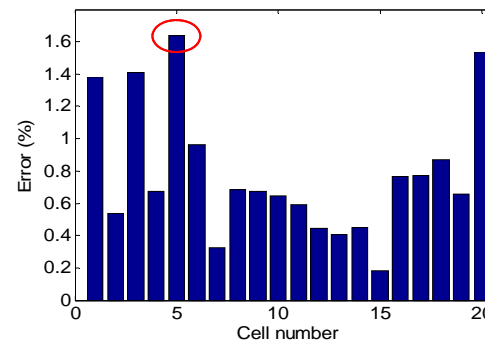
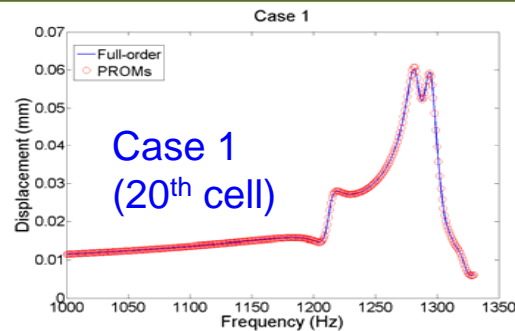
Forced response of 18th cell



Numerical Results: PROMs

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION



Reduced-DOFs: 25

Maximum error: ○

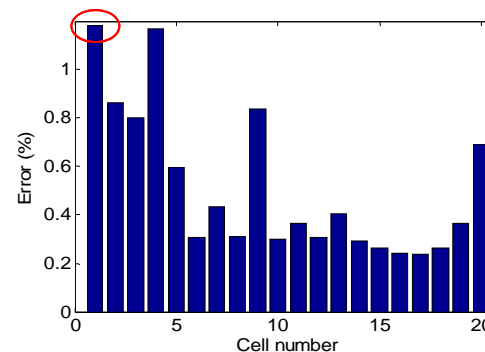
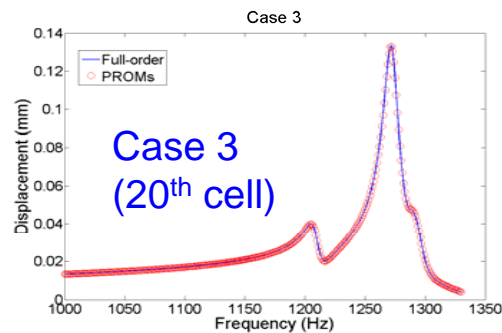
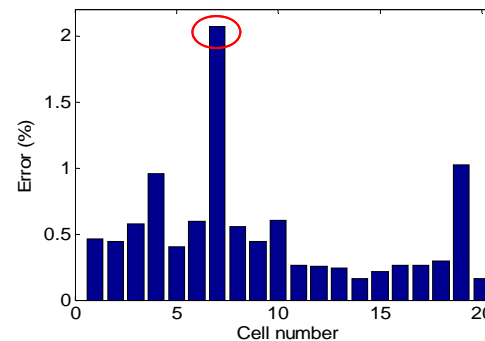
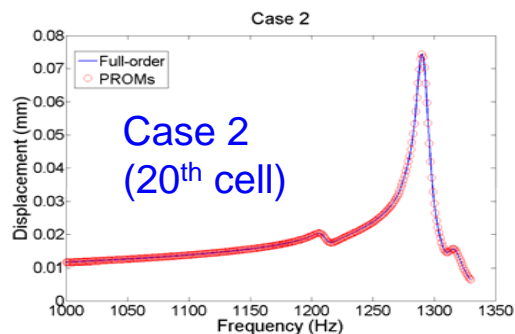
Case 1: 1.64%

Case 2: 2.07%

Case 3: 1.18%

CPU time for reanalysis:

0.71 - 0.85 sec

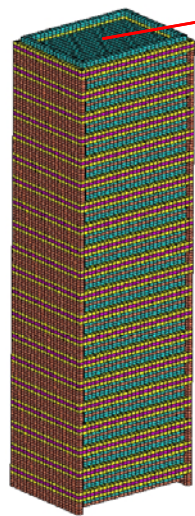


PROM reanalysis is
9,000 times faster than
that of full-order model

Numerical Results: Detection of Highest Vibrating Cells

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

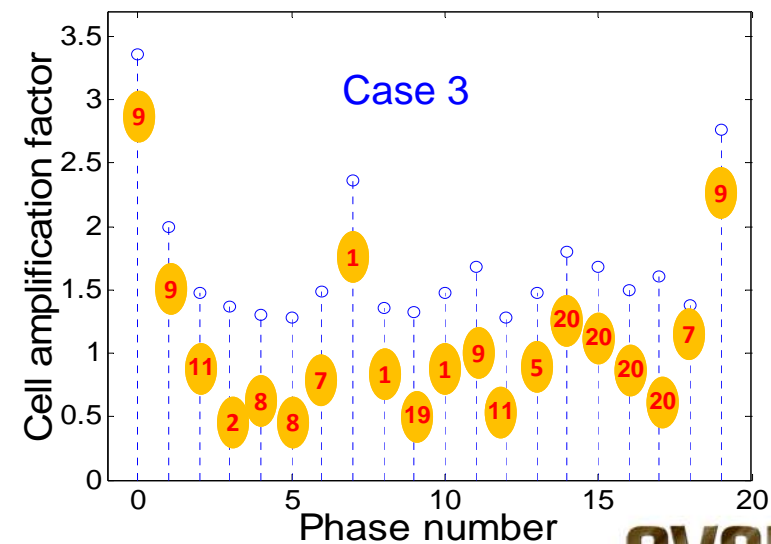
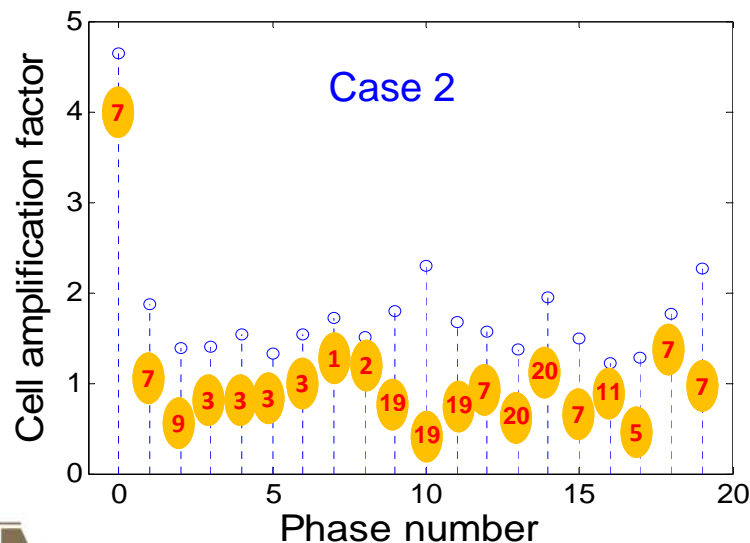
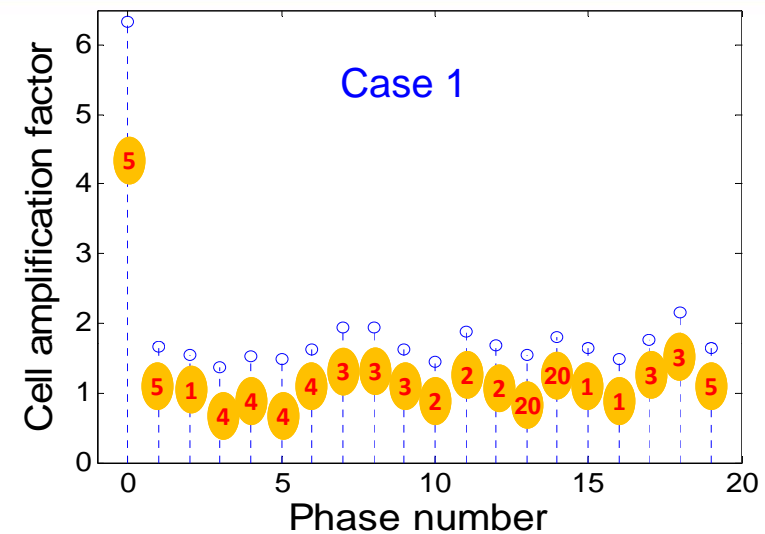


Traveling wave excitation to the center nodes of each battery cell

Cell amplification factor (CAF)

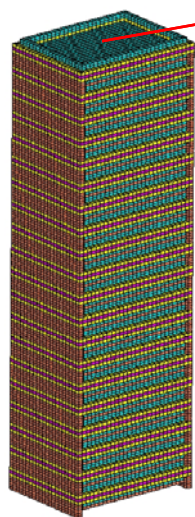
$$CAF_k^j = \max_{i=1, \dots, 20} \left(\frac{\max_{\omega} (|A_i| \Delta p)}{\max_{\omega} (|A_i|^{\text{Nominal}})} \right)$$

#: Highest vibrating cell for each phase



Numerical Results: Statistical Analysis

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION



Traveling wave excitation applied to center nodes of each battery cell

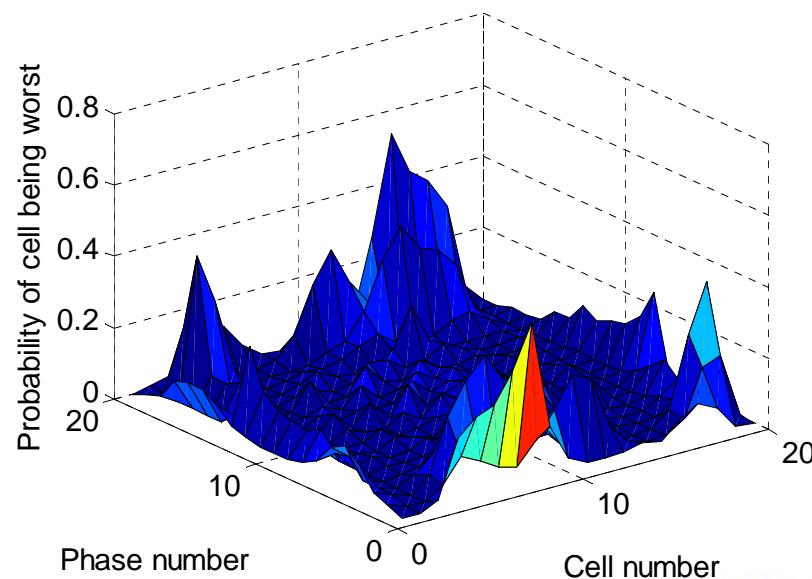
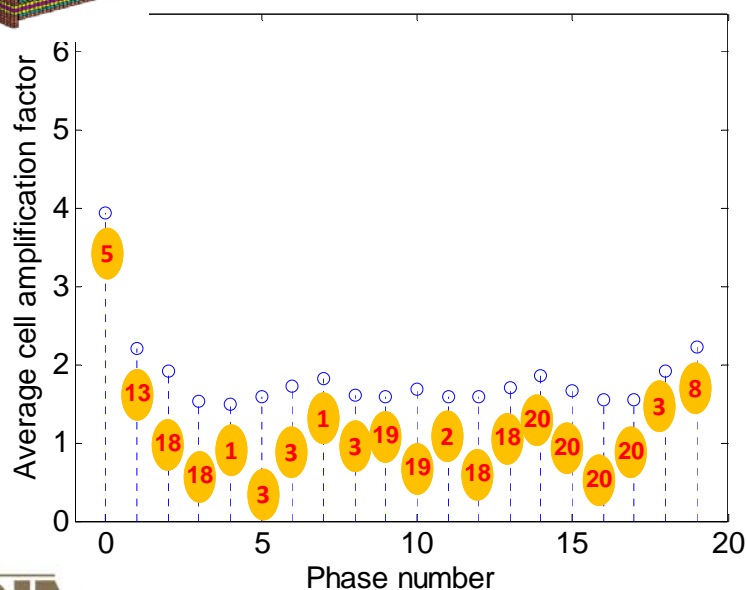
Average CAF:

$$CAF_k^j(\text{AVG}) = \max_{i=1, \dots, 20} \left(\frac{1/10,000 \sum_{j=1}^{10,000} \max_{\omega} (|A_i|^{\Delta p})}{\max_{\omega} (|A_i|^{\text{Nominal}})} \right)$$

10,000 cases of elastic modulus variation to all 20 cells

Analysis time: 0.8 sec × 20 phases × 10,000 cases = 160,000 sec (44 hours)

: Statistically highest vibrating cell for each phase





Conclusions

MSTV

MODELING AND SIMULATION, TESTING AND VALIDATION

- **Introduced efficient structural dynamic simulation** capability for HEV batteries
 - Enables **fatigue life prediction**
- **Developed parametric reduced-order models** (PROMS) to capture dynamic response very quickly for structures featuring **high modal density**
 - **Reanalysis time** of new PROMs for each variation is **9,000 - 10,000 times faster** than that of full-order models
- Identified the **weakest cell (highest vibration)** by using **statistical analysis** based on cell amplification factors